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INTERACTION BETWEEN ELECTROMAGNETIC WAVES AND FLAMES

PART 3 - ABSORPTION LOSS THROUGH ROCKET EXHAUSTS AS A FUNCTION OF ALTITUDE

[UNCLASSIFIED TITLE]

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Radar Techniques Branch
Radar Division

May 1, 1957

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NAVAL RESEARCH LABORATORY
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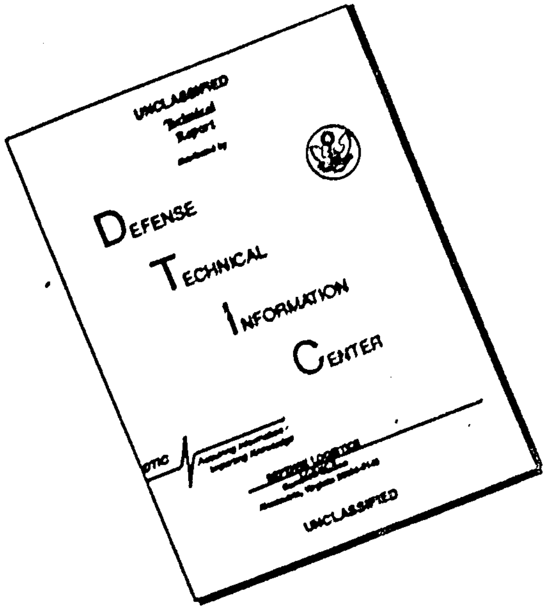

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CONTENTS

ABSTRACT
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An 11-lb-thrust rocket motor using ethyl alcohol and oxygen has been operated successfully in the NRL simulated-altitude chamber at ambient pressures down to 2 mm. This type of operation has greatly simplified taking quantitative measurements on a rocket-motor exhaust at various simulated altitudes up to 130,000 feet. The transverse electromagnetic wave absorption by the rocket exhaust decreases with increasing simulated altitude, decreases with an increase in the frequency of the incident electromagnetic wave, and increases with the amount of some easily ionized fuel additives. Incident frequencies corresponding to wavelengths of 0.84, 1.24, and 3.2 cm were used. Photographs show the rocket-exhaust structure at 17 simulated altitudes from sea level to 130,000 feet.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

NRL Problem R07-07
Projects NR 418-000 and 418-005
AF--MIPR-550WDD-2

Manuscript submitted January 28, 1957

INTERACTION BETWEEN ELECTROMAGNETIC WAVES AND FLAMES PART 3 ABSORPTION LOSS THROUGH ROCKET EXHAUSTS AS A FUNCTION OF ALTITUDE [Unclassified Title]

INTRODUCTION

Extensive investigations of the propagation of electromagnetic waves through rocket-motor exhausts have been conducted on captive engines operating at sea level (1,2). Quantitative measurements on rocket exhausts in high-altitude flight are difficult to make and available information even related to this phase is sketchy and extremely difficult to interpret. This situation prompted a preliminary study by the Naval Research Laboratory of rocket flames as a function of altitude, which was conducted with a very small rocket motor in an available simulated-altitude chamber (3). Early experiments with this method appeared promising, and a program was instituted to:

(1) increase the exhaust rate capabilities of the simulated-altitude chamber,

(2) install a larger rocket motor in the chamber, and

(3) develop a suitable electromagnetic probe system for studying the electromagnetic absorption of a small rocket exhaust.

Since the completion of most of these facilities considerable experimental data have been gathered giving absorption loss of microwave signals through a flame diameter as a function of altitude and some fuel parameters. In addition, some spectral emission and temperature measurements on the flame have been made (4).

SCOPE OF REPORT

This report presents the magnitude and change in the electromagnetic wave absorption by a rocket flame as a function of back pressure or simulated altitude, frequency of incident energy, and the quantity of some easily ionized fuel additives. Data are presented for the incident frequencies corresponding to wavelengths of 0.84 and 1.24 centimeters over the simulated-altitude range of 20,000 to 130,000 feet (325 to 2 mm of mercury). Absorption data on 3.2-centimeter wavelength are also included for ambient back pressures up to only 100 mm of mercury. All of these data with an explanatory introduction are presented for reference as the content of Appendix A of this report. Appendix B, with its explanatory introduction, shows a series of photographs of a rocket-motor flame as a function of altitude. These photographs, in conjunction with Figure 10, which portrays the position of the first shock diamond as a function of simulated altitude, show the geometrical growth as well as the position in the flame where quantitative absorption data were taken.

EXPERIMENTAL EQUIPMENT

The electronic system used to determine the electromagnetic wave absorption versus altitude data is shown in Fig. 1 and is similar to that described in previous reports (5,9). The source magnetron is modulated with 1/4 microsecond pulses at a rate

of 960 a second and its electromagnetic energy is passed through the flame in a direction perpendicular to the flame axis, that is, through a flame diameter, and restrained from other paths by means of horn-lens focusing antennas (6). The signals are detected, amplified, passed through a scale expander, averaged, and then permanently displayed by a Sanborn Recorder. A padded calibrated precision attenuator in the transmitting wave guide provides, by substitution of successive attenuation reference levels, a calibration of the system. The antenna rack assembly which holds the horns at a fixed separation (Fig. 4) can be moved in a known manner along (i.e., parallel to), the flame axis.

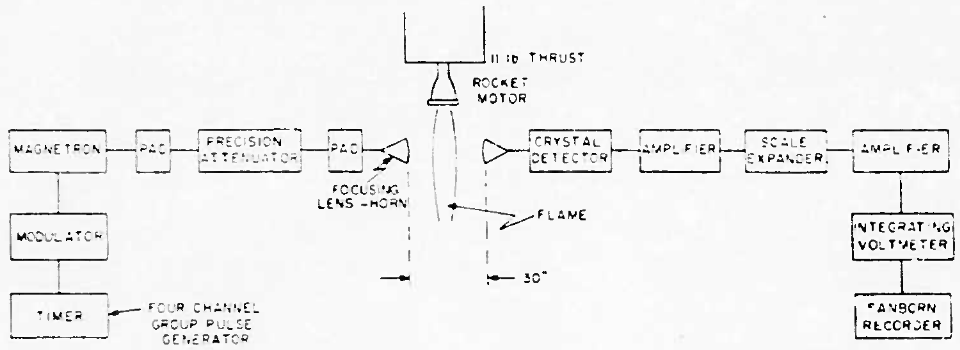

Fig. 1 - Electromagnetic flame probe system

The rocket motor, its fuel and oxidizer tanks, and control system were made under contract by Reaction Motors Incorporated (7). The motor is nominally rated at 11-pound thrust when operating with a combustion chamber pressure of 300 pounds per square inch. A cross section of the nozzle of this motor is shown in Fig. 2.

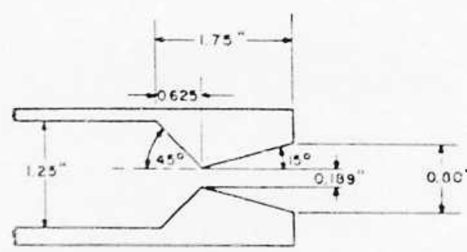

Fig 2 - Eleven-pound-thrust rocket motor nozzle

Liquid oxygen and ethyl alcohol make up the propellant combination normally used, but with this oxidizer-fuel combination electromagnetic absorption with the altitude chamber evacuated to an equivalent high altitude is so small as to reduce the accuracy of attenuation measurements. As a consequence, low-ionization-potential fuel additives

are used to enhance the ionization of the exhaust. In particular, known amounts of sodium, potassium, and cesium salts dissolved in the alcohol served to enhance and control the number of free electrons in the exhaust. For the series of altitude experiments here reported, fuel and oxidizer rates were adjusted for the best rocket motor operation, and were held essentially constant from run to run.

The simulated-altitude chamber referred to previously is a product of the Guardite Company, and was initially intended to provide variable conditions of altitude, temperature, and humidity for determining the performance of airborne equipments. The available chamber work space is approximately 6 by 7 by 7 feet. Its original exhaust pumping system has been enlarged by the addition of four Ingersoll-Rand steam ejector stages and associated condensers and cooling capacity, so that 200 pounds of exhaust gases from the rocket per hour can be handled at any desired altitude within the redesigned range. The ambient pressure range available under these conditions is from 760 to 2 mm of mercury, corresponding to altitudes from sea level to 130,000 feet. Figure 3 is a picture of the steam ejector addition that makes this altitude range possible at the 200-pounds-per-hour exhaust rate.

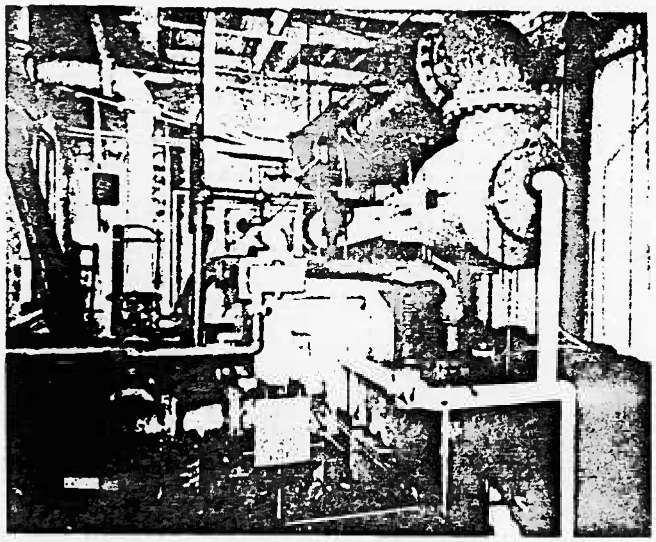

Fig. 3 - Steam ejector pumping system

Figure 4 shows the interior of the simulated-altitude chamber with the antenna rack and rocket motor in position. The lens-fitted horn antennas for transmitting and receiving are shown in line with the flame axis. The antenna rack is provided with a drive mechanism (shown on the left), that allows travel along or parallel to the flame axis at a rate of approximately 3 inches per second. A position marker signal is generated for every inch of travel for the purpose of identifying the data. This equipment is actuated and controlled from without the chamber. In Fig. 5, the data recording equipment is shown on the left and the rocket-motor manual-control panel on the right. The fuel cells (not shown), are to the rear of the altitude chamber, which is to the immediate right of the motor-control panel.

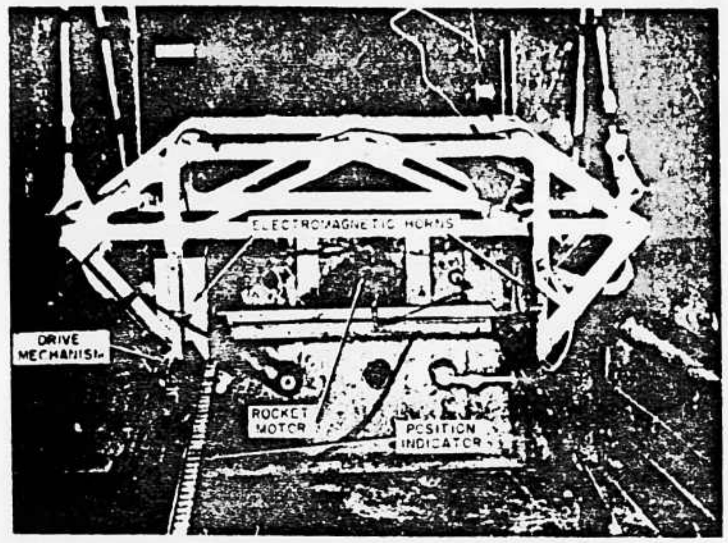

Fig. 4 - Interior view of altitude chamber showing traveling rack carrying the electromagnetic probes

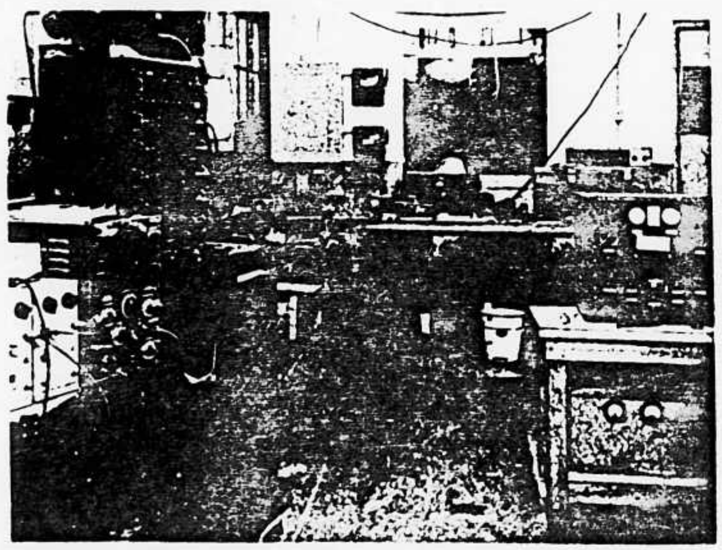

Fig. 5 - Data recording and rocket motor control panel

MEASUREMENT PROCEDURE

With the signal generating, transmission, and detecting system of the desired wavelength in operation, the sensitivity is adjusted without the interposed flame to accomodate the expected signal level. The altitude chamber is then pumped down to the desired simulated altitude and the electronic system (Fig. 1), is calibrated by means of the precision attenuator. With this preparation, the rocket motor is ignited and adjusted for stable fuel flow and burning operation, after which the flame is traversed down its length by the antenna rack while the desired data are taken. After the rack has traversed the flame length, the rocket motor is turned off and the electronic system again calibrated. The main data, insertion loss, electromagnetic focus position, and calibration data are all permanently recorded on the Sanborn Recorder. It was pointed out that the observed values of loss with this system are very small, and fuel additives were used to enhance the observed loss values. This does not produce fictitious data because a plot of loss versus contaminant concentration is of the normal form.

CONDENSED EXPERIMENTAL RESULTS

Signal loss measurements through a flame diameter at wavelengths of 0.86 and 1.24 cm have been made as a function of ambient pressures up to 325 mm. At an operating wavelength of 3.2 cm, the highest practical pressure used was 100 millimeters. For pressures above the values 325 mm with 0.86-cm and 1.24-cm signals and 100 millimeters with 3.2-cm signal, the flame dimensions neared the point where some of the focused energy by-passed the flame, rendering the data interpretation difficult.

For all measurements the electromagnetic waves were focused by the horn-lens system on the flame and their transit through the flame was on a diameter normal to the flame axis. Effects due to reflection at the flame boundary and ionization by the incident electromagnetic waves are considered negligible on the basis of other work performed in the past but not reported herein.

The information revealed by an extensive series of simulated altitude experiments is that the maximum absorption expressed in db for 0.86-and 1.24-cm waves through a flame diameter is approximately linear with ambient pressure over the exhaust pressure range of 0 to 325 mm of mercury. The maximum absorption referred to is obtained by traversing the length of the flame and picking the point of maximum loss, a point which moves farther down the flame from the rocket motor throat with decreasing ambient pressure. It is also noted that the same linear relationship between db loss through a flame diameter and ambient pressure holds for other points through the flame, such as the sixth shock diamond, etc. These observed absorption trends for signals of 0.86- and 1.24-cm wavelengths are shown in Figs. 6 and 7 respectively. Both figures show loss curves for fuel additives of cesium, potassium, and sodium acetate in the amount noted. In Fig. 8, maximum absorption loss for 3.2-cm signals is given with ambient pressure. As mentioned earlier, this pressure range is limited by the larger focal area of the electromagnetic system at this wavelength.

Since the absorption for 0.86-, 1.24-, and 3.2-cm waves is not greatly different at sea level ambient pressures, (2, 8) it is evident that the linear relationship between db loss through a flame diameter and ambient pressure cannot hold for 3.2-cm waves except at very low pressures.

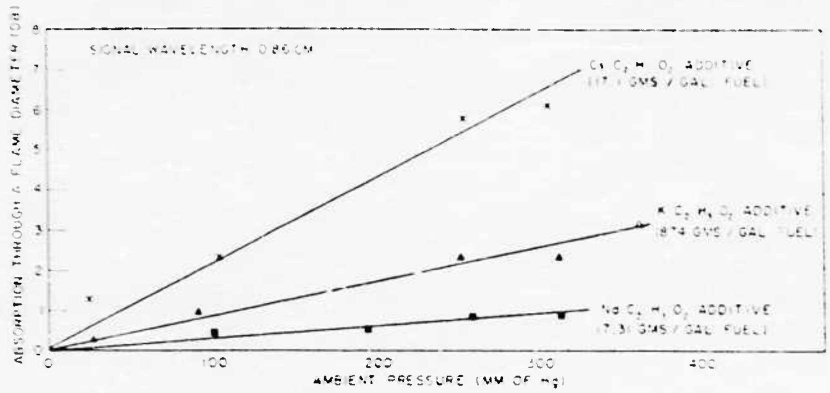

Fig. 6 - Signal absorption as a function of ambient pressure for three different fuel additives

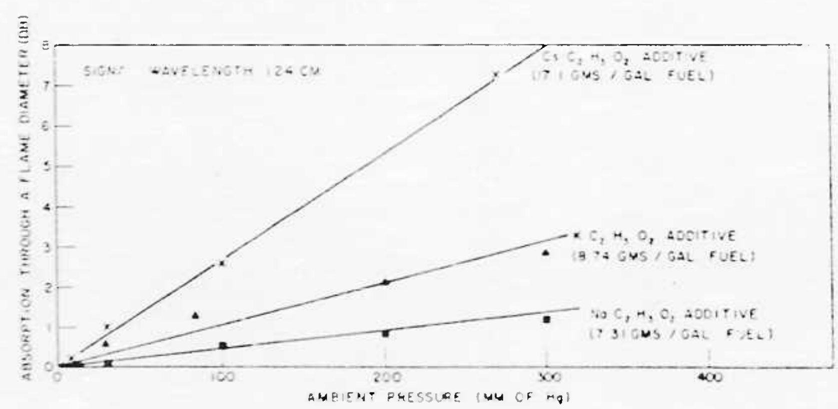

Fig. 7 - Signal absorption as a function of ambient pressure for three different fuel additives

Figure 9 is a plot of normalized absorption loss through a flame diameter as a function of ambient pressure and is based on the measurements with 0.86- and 1.24-cm wavelength signals. As such it gives the cross flame absorption for any position down the flame relative to the absorption at an ambient pressure of 300 mm of mercury at the equivalent position -- the equivalent position, for example, being through the same shock diamond.

To a fair approximation, all dimensions of the flame show the same size dependence on ambient pressure. This characteristic is demonstrated in Fig. 10, which gives distance from the exit plane and first shock diamond as a function of ambient pressure. Included on the figure is a theoretical curve computed from simple expansion theory. Based on this type of data, a normalized plot of flame-size-versus-ambient-pressure is given in Fig. 11. This plot is a good representation of growth down the axis of the flame, and a fair approximation of flame-diameter variation with ambient pressure.

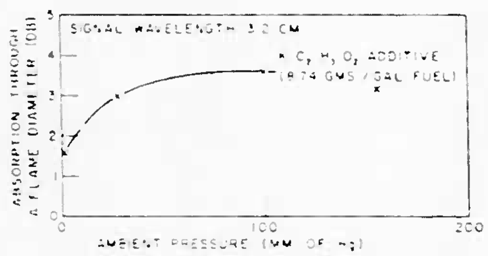

Fig. 8 - Signal absorption as a function of ambient pressure and with potassium acetate fuel additive

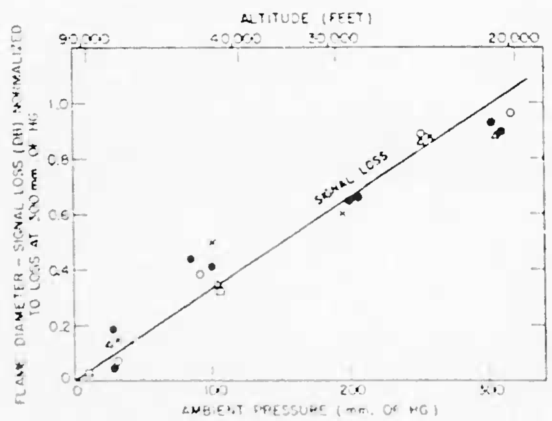

Fig. 9 - DB signal loss (normalized to loss at 300 mm) versus ambient pressure in millimeters

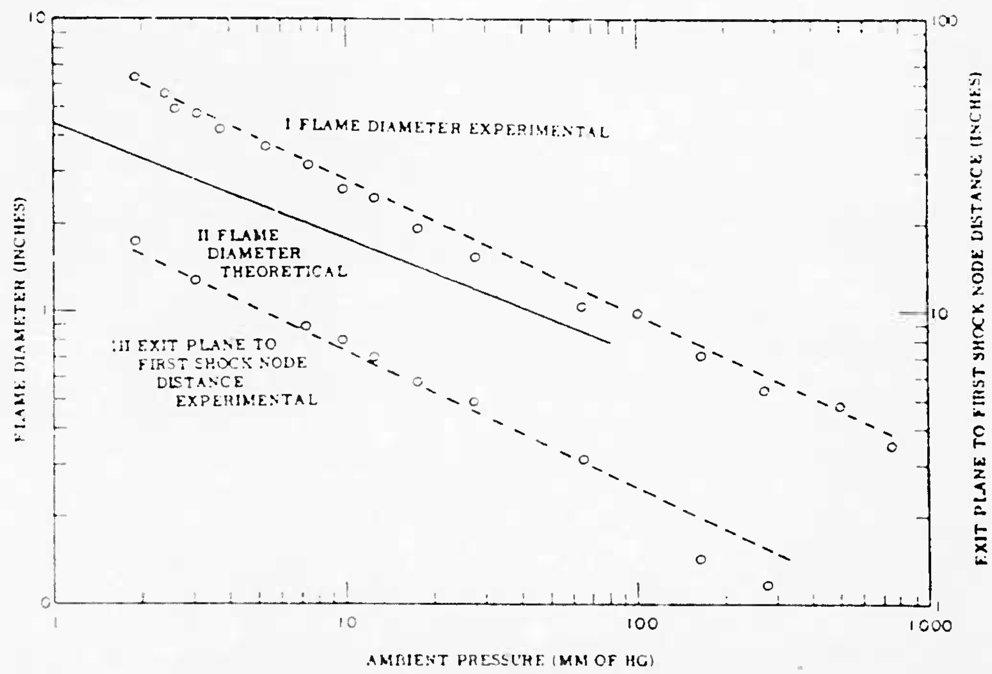

Fig. 10 - Flame diameter growth with ambient pressure; I - experimental, II - theoretical, III - exit plane to first shock diamond distance as a function of ambient pressure

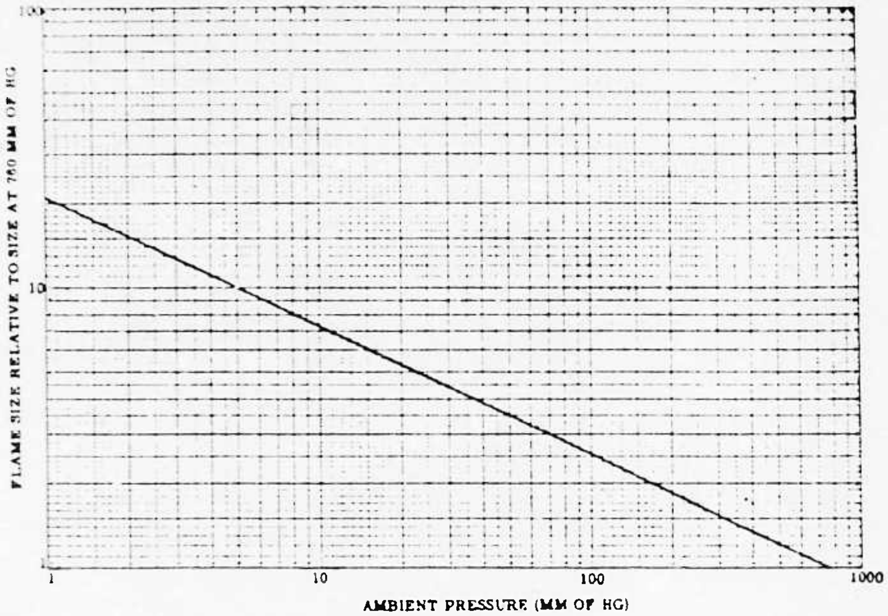

Fig. 11 - Relative flame size versus ambient pressure

CONCLUSIONS

Electromagnetic absorption loss through the rocket exhaust has been found to decrease with increasing altitude at wavelengths of 0.86, 1.24, and 3.2 cm. For the 0.86- and 1.24-cm wavelengths, maximum absorption in db is approximately a linear function of ambient pressure over the range of 0 to 300 mm of mercury.

Although the influential flame boundaries are not well defined, and free electron distribution throughout the flame is not completely known, it is possible to estimate good first-approximation loss figures for various paths through the flame over a range of altitudes.

ACKNOWLEDGMENT

Efficient operation of a small rocket motor in an altitude chamber requires a high degree of team work between those who take the data, the rocket motor operator, and the personnel who operate the chamber. The authors acknowledge the excellent work of Mr. H. C. Helms of the Refrigeration Section, NRL Public Works, who is in charge of the altitude chamber operations; and of Mr. Earl Ward of the Radar Techniques Branch, who operates the rocket motor.

* * *

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APPENDIX A
Rocket Exhaust Absorption Characteristics as a Function of Ambient Pressure

This appendix details cross-flame absorption characteristics as a function of distance down the flame axis for various ambient pressures and for several degrees of different fuel contaminants. The data presented in Fig. A-1 through A-8 are identified as follows:

FIGURE	SIGNAL WAVELENGTH (cm)	FUEL ADDITIVE
A-1	1.24	CsCl
A-2	1.24	$CsC_2H_3O_2$
A-3	1.24	$KC_2H_3O_2$
A-4	1.24	$NaC_2H_3O_2$
A-5	0.86	$CsC_2H_3O_2$
A-6	0.86	$KC_2H_3O_2$
A-7	0.86	$NaC_2H_3O_2$
A-8	3.2	$KC_2H_3O_2$

These data are the source of material for the plots in Figs. 6, 7, 8, and 9. One statement of explanation is in order; at ambient pressures where the compression and rarefactions down the exhaust stream caused a pronounced wave-like character in the absorption down the flame, average maximum absorption values were selected instead of peak values.

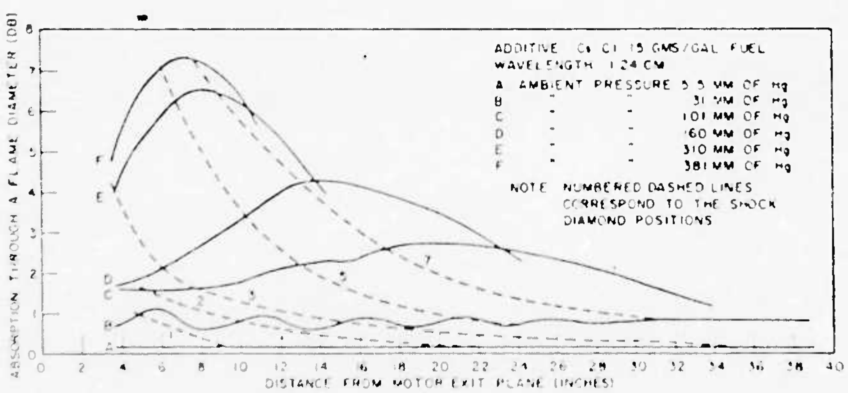


Fig. A-1 - Absorption through a flame diameter versus distance from motor exit plane for several ambient pressures

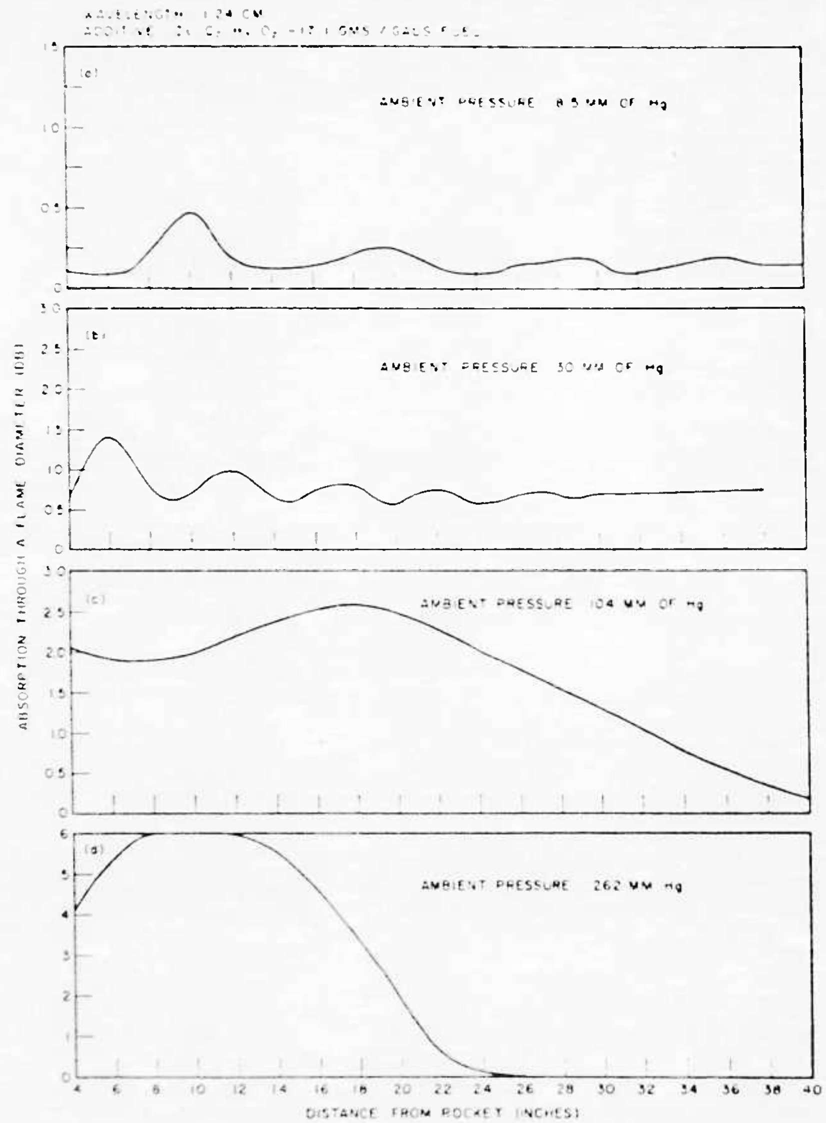


Fig. A-2 - Absorption through a flame diameter versus distance from rocket motor for several ambient pressures

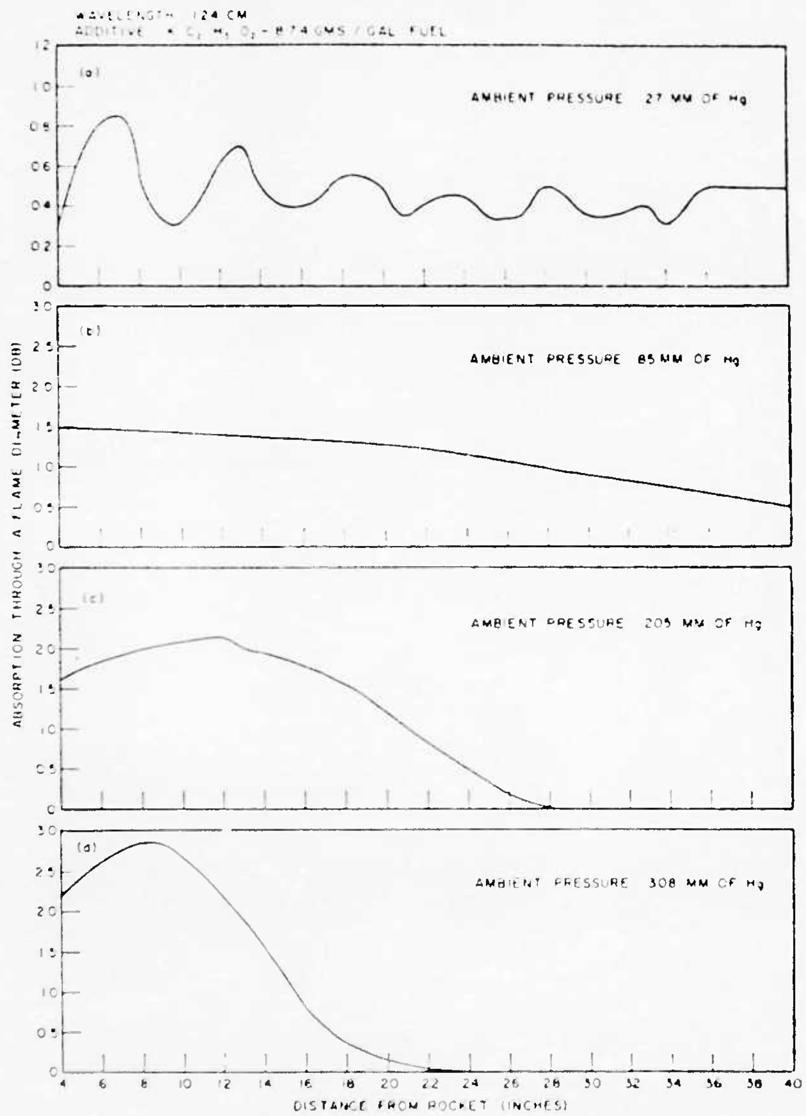


Fig. A-3 - Absorption through a flame diameter versus distance from rocket motor for several ambient pressures

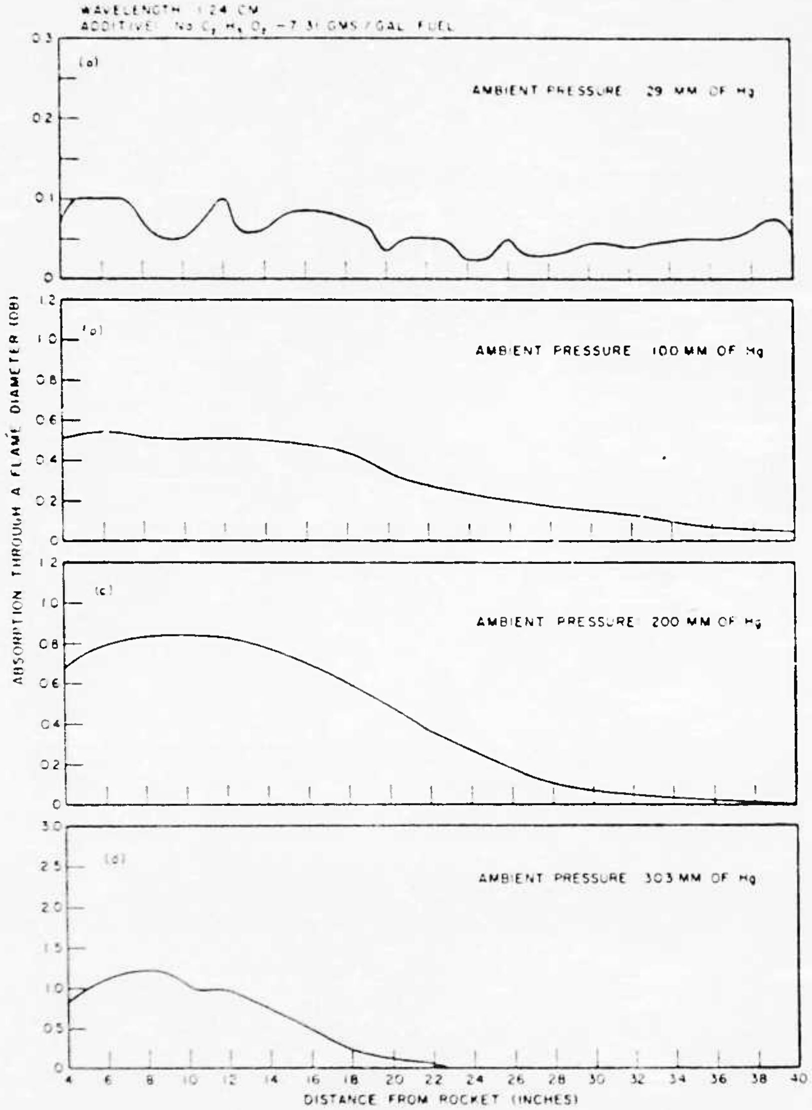


Fig. A-4 - Absorption through a flame diameter versus distance from rocket motor for several ambient pressures

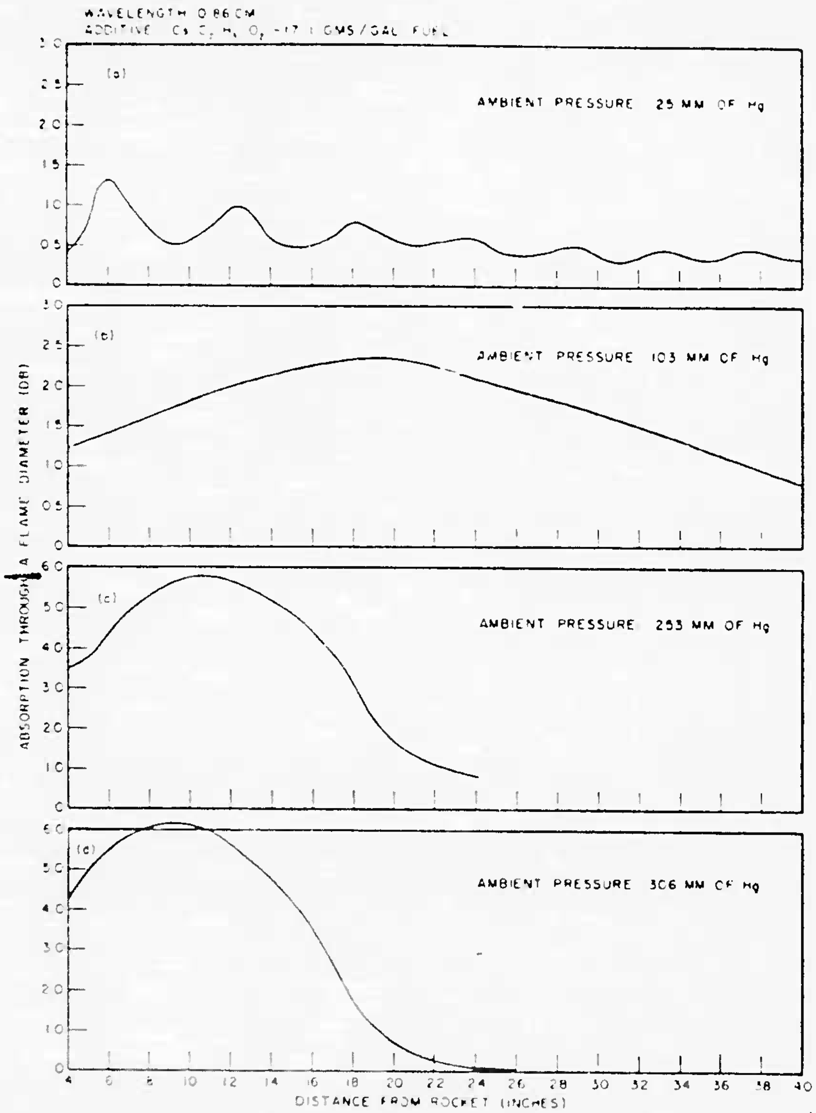


Fig. A-5 - Absorption through a flame diameter versus distance from rocket motor for several ambient pressures

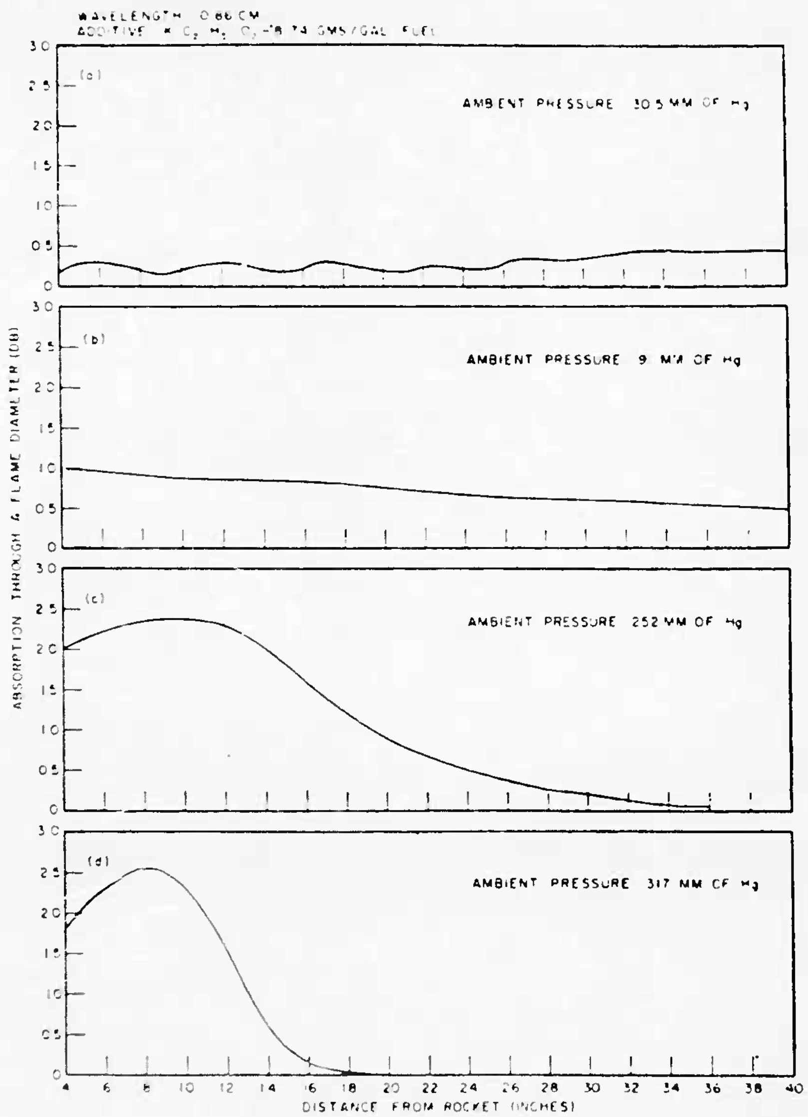


Fig. A-6 - Absorption through a flame diameter versus distance from rocket motor for several ambient pressures

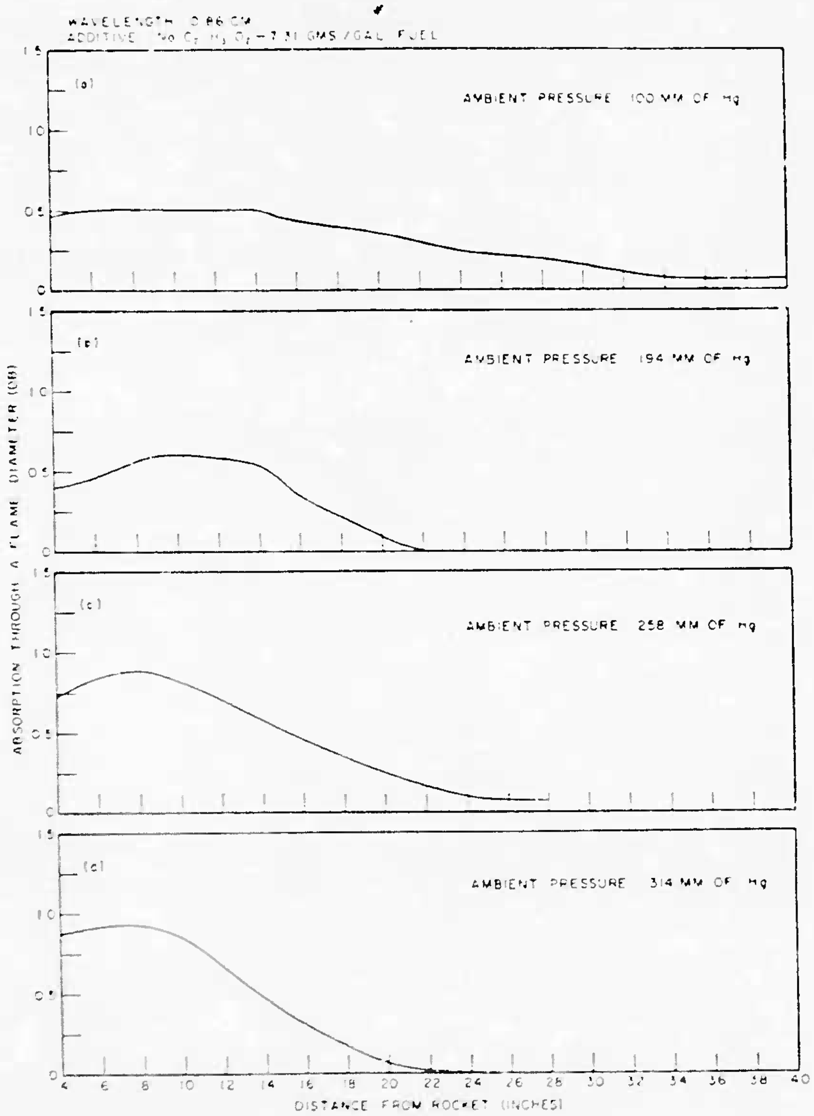


Fig. A-7 - Absorption through a flame diameter versus distance from rocket motor for several ambient pressures

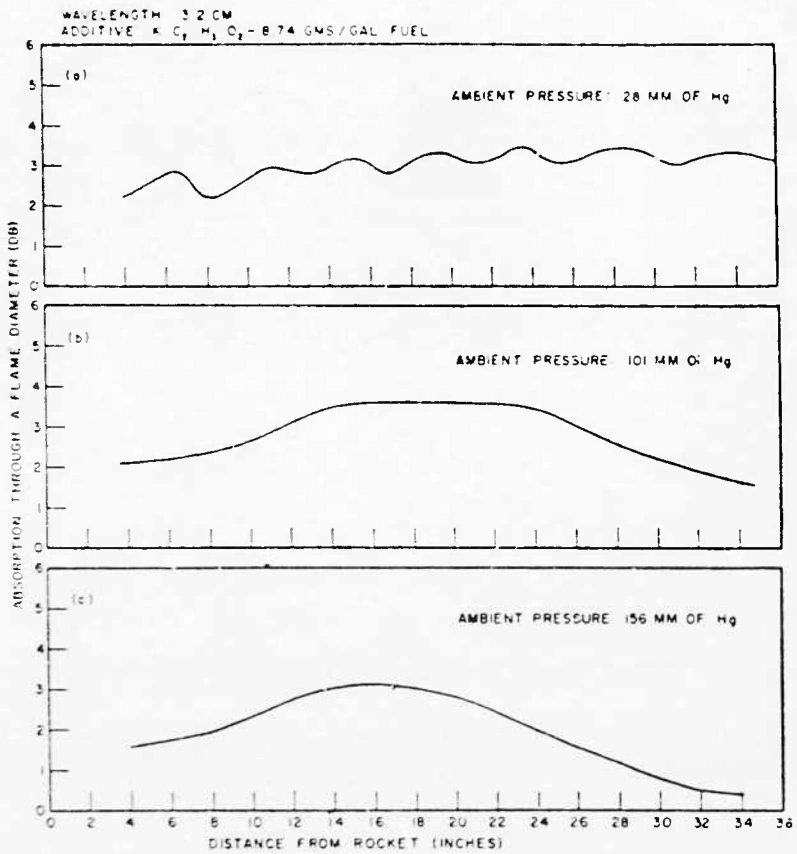
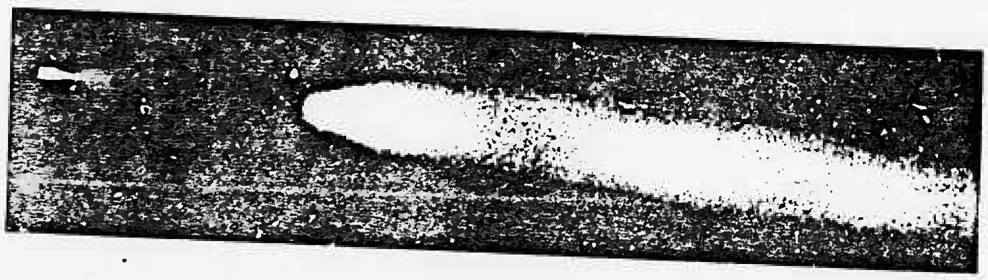


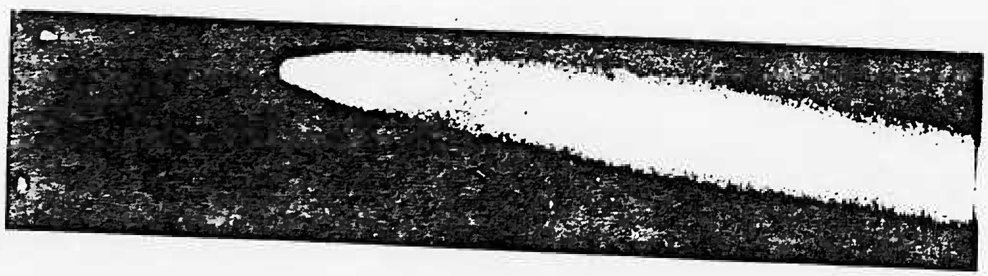
Fig. A-8 - Absorption through a flame diameter versus distance from rocket motor for several ambient pressures

APPENDIX B
Rocket Exhaust Geometry versus Altitude

This appendix shows 18 pictures, Fig. B-1 including a dimensional reference picture of an 11-lb-thrust rocket motor exhaust at various ambient back pressures. From the negatives of pictures such as these, dimensional growth of the exhaust with ambient pressure (or simulated altitude) was determined for Fig. 10 and 11. Included in this appendix is a family of curves, Fig. B-2, of position for various parts of the exhaust versus ambient pressure reduced from the pictures. Also a curve, Fig. B-3, is included for converting from ambient pressure to simulated altitude.



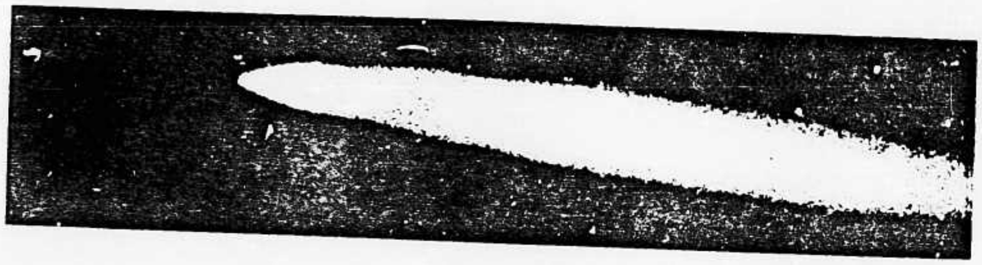
a - 132,000 feet



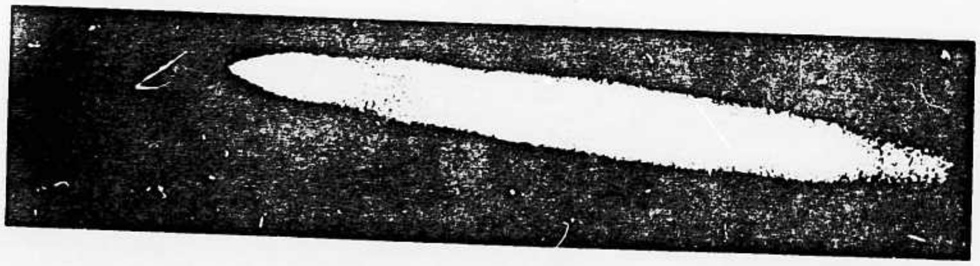
b - 126,000 feet

(Fig. B1 - continued)

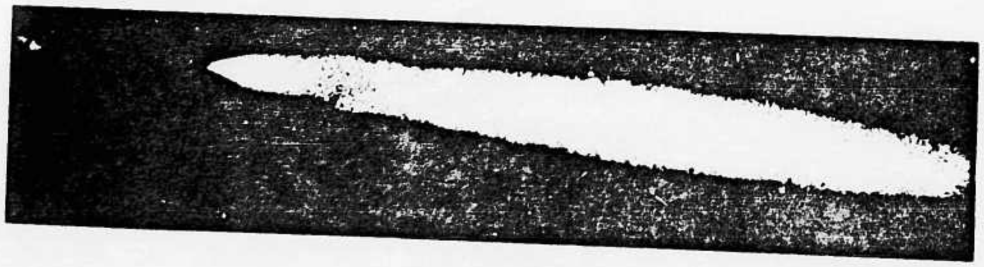
c - 124,000 feet



d - 119,000 feet

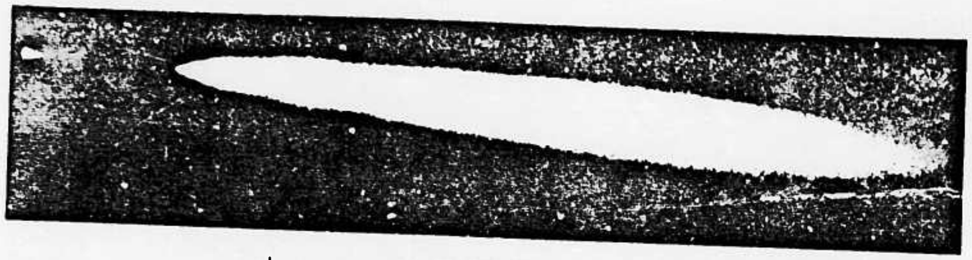


e - 114,000 feet



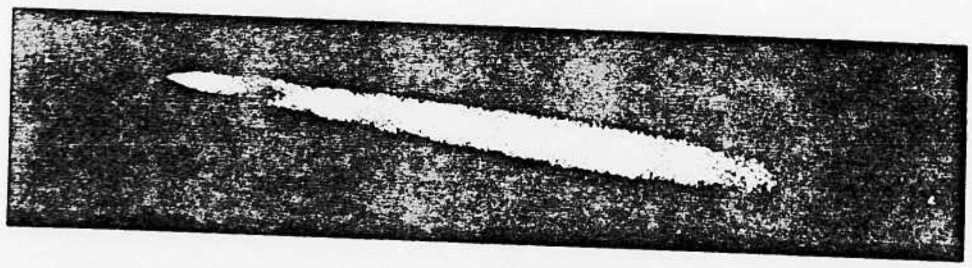
f - 106,000 feet

(Fig. B1 - continued).

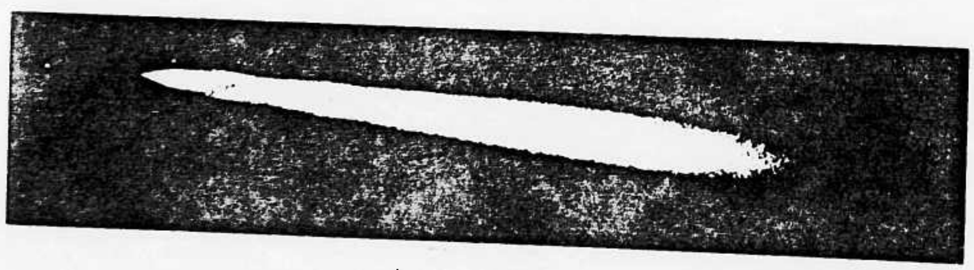


g - 96,000 feet

h - 90,000 feet

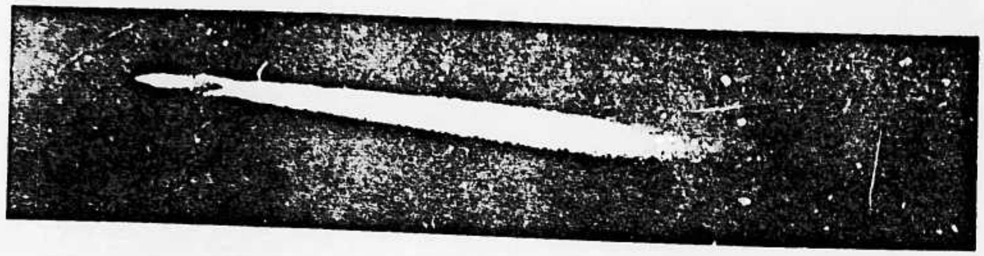


i - 84,000 feet

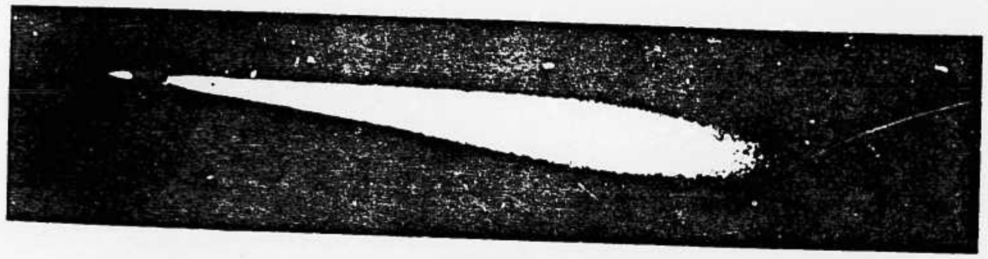


j - 77,000 feet

(Fig. B1 - continued)

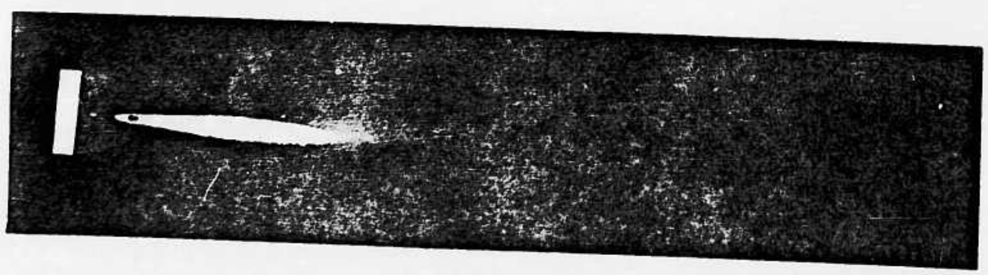


k - 70,000 feet



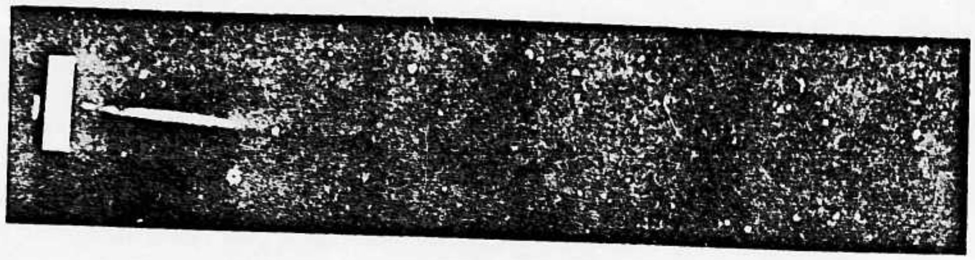
l - 53,000 feet

m - 33,000 feet



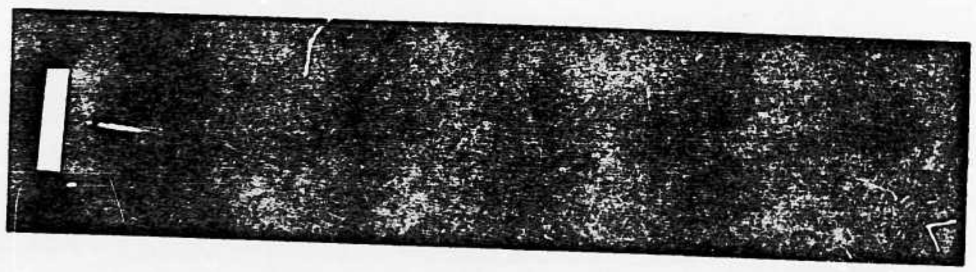
n - 22,000 feet

(Fig. B1 - continued)

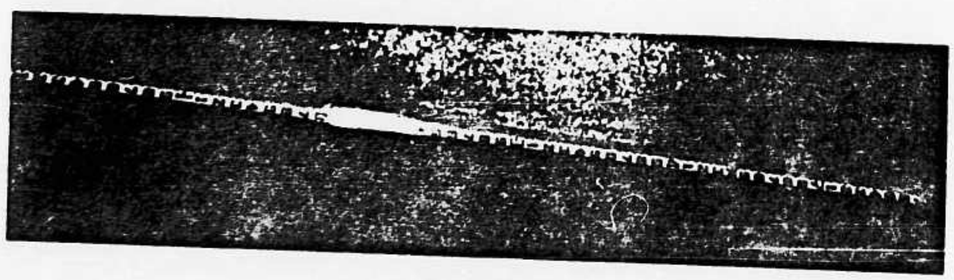


o - 17,000 feet

p - 9,000 feet



q - Sea level



r - Stadia reference

Fig. B1 - Rocket exhaust structure as a function of altitude

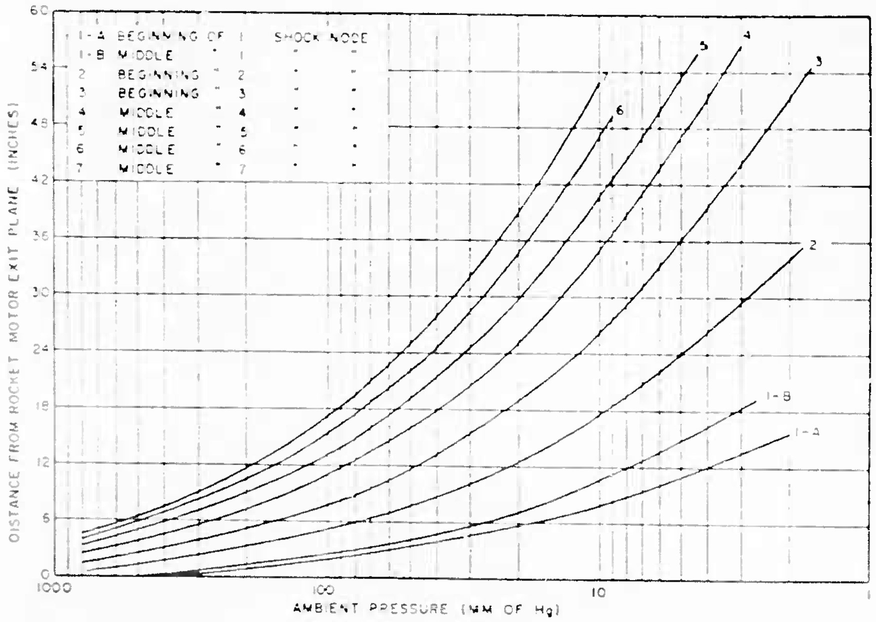


Fig. B-2 - Position of shock diamond versus ambient pressure

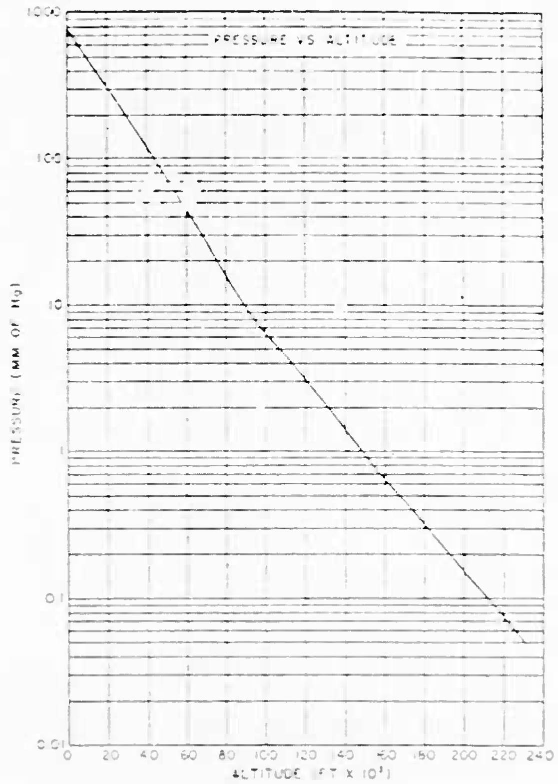


Fig. B-3 - Pressure as a function of altitude